



Fermi National Accelerator Laboratory

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End Designs for Superconducting Magnets

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New accelerators such as the Tevatron Upgrade frequently require higher magnetic fields than have been conventionally used in superconducting magnets. Modern magnet designs often have a smaller bore diameter and wider cable than the early (e.g., Tevatron) superconducting coils and are consequently harder to wind. These developments make consideration of end winding more important. End parts must be made to confine the conductors to a consistent shape. This shape must be defined and described to both the parts manufacturers and those analyzing the magnetic field. Internal stresses in the cable must be minimized. It has therefore become necessary to reevaluate the methods used to determine the configuration of a magnet end. This note describes those methods and attempts to apply them to possible cross sections for high field dipoles. The original Tevatron dipole end configuration is reviewed for reference.

The Tevatron End

Over one thousand Tevatron magnets have been produced at Fermilab. The path which the conductors take as they are wound around the ends on these magnets is defined as the intersection of a sphere and a cylinder (see Figure 1). It can be generated by simply drawing a circle with a compass on the surface of a cylinder. At the center of each turn the cable is held vertical, that is, perpendicular to the beam path in the yz plane (see Figure 1). This shape has the advantage of being easy to define and inspect. The disadvantage of the "vertical" end is that it results in high internal stresses in the cable. These stresses, although high, were within acceptable limits on the Tevatron magnets. The Tevatron bore diameter is three inches.

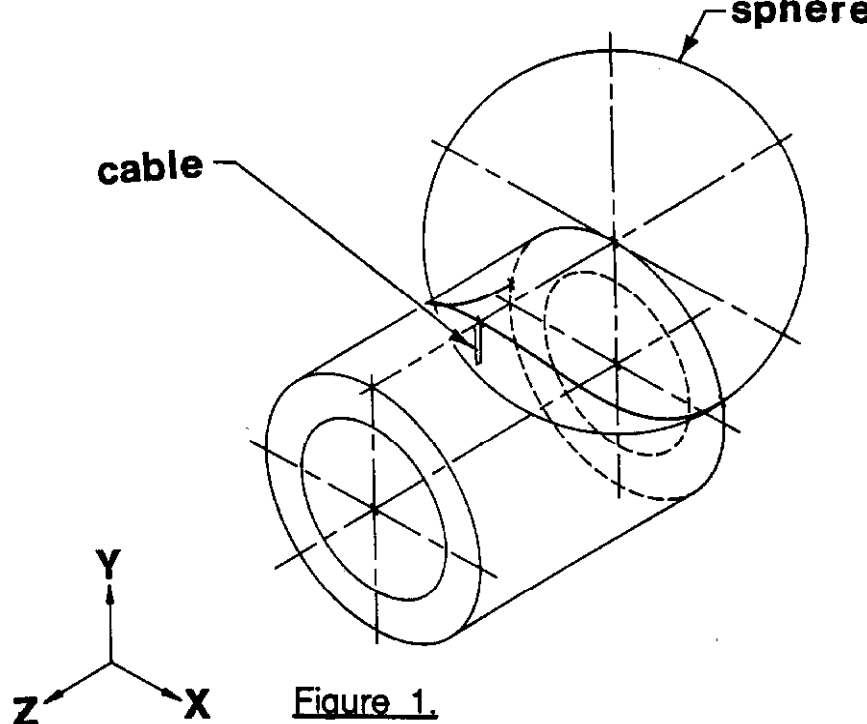


Figure 1.

Internal stresses in the cable as it is wound around the end increase as the bore diameter becomes smaller. They also increase as the cable gets wider. This is because a large portion (we believe the majority) of the stress in the cable is induced by the "bend the hard way" (see Figure 3). Stresses from this bend get increasingly larger as the bore gets smaller and as the cable gets wider. Many of the magnets now being designed and built have smaller bore diameters and wider cable than the Tevatron. As a result ends which are wound using the Tevatron techniques may have unacceptably high stresses. These stresses create many problems.

A. Turn-to-turn shorts.

Cables which are forced into an unnatural path can cause breakdown of the kapton insulation between turns.

B. Degradation of Strands.

High stresses cause the strands to stretch, and in the worst cases, break. Strands will also come "out of lay" causing the cable to take a shape other than it's intended keystone shape.

C. Difficult to Wind.

D. Difficult to maintain magnet-to-magnet consistency in conductor placement.

E. Tendency of turns to move into the bore after curing.

The cable tries to take a position which is less stressful than that into which it was wound. This usually results in the inner coil turns moving into the bore area (see Figure 2).

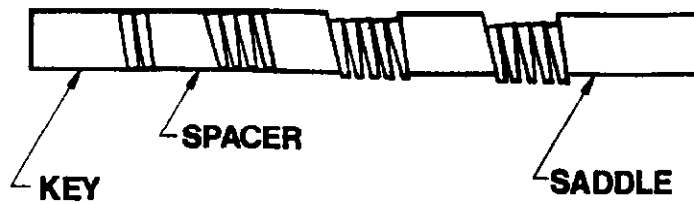


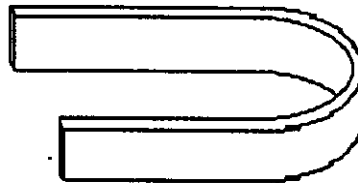
Figure 2.

A new end design has been developed which reduces the stress in the cable as it is wound around the end.

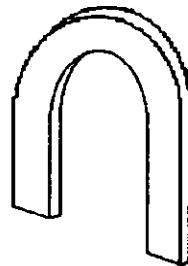
The initial premise:

The cable, as it is wound around the end of a magnet, is subject to stresses in three ways:

- 1.) It is bent "the easy way".



- 2.) It is bent "the hard way"



- 3.) It is twisted.

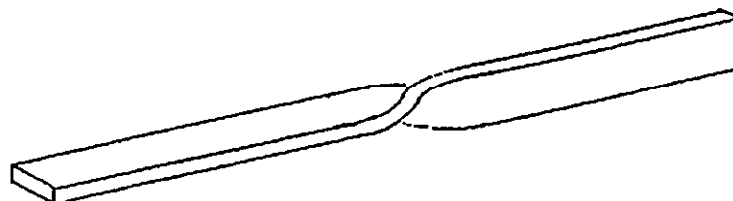


Figure 3. Cable Deformations

If we assume these deformations are elastic, each is accompanied by a corresponding increase in strain energy.

The present end program is based on the assumption that the "bend the hard way" is the primary contributor to the stress in the cable. This seems intuitively obvious when one bends a cable by hand but needs to be proven.

It is possible to eliminate the bend the hard way by creating a developable surface which, when "unwrapped", is bounded by a straight line. The straight line represents the unwrapped base curve. Using the developable surface does not eliminate all the stress in the cable. The strip is still bent the easy way and twisted.

A program has been written by Joe Cook of Argonne National Lab which creates end winding paths by using a developable surface.

The procedure:

1.) A base curve is created. The base curve is defined as the path which one edge of the conductor takes as it is wound around the end of a coil. It is represented by a one dimensional line in three dimensional space.

The base curve may be placed on either the inside or outside radius of the layer. Fermilab coils use the outside radius. This allows the gap on the inside radius to be used to provide internal support for the conductor. A "shelf" is attached to the spacer, filling the empty space and keeping the turns from moving into the bore (see Figure 4).

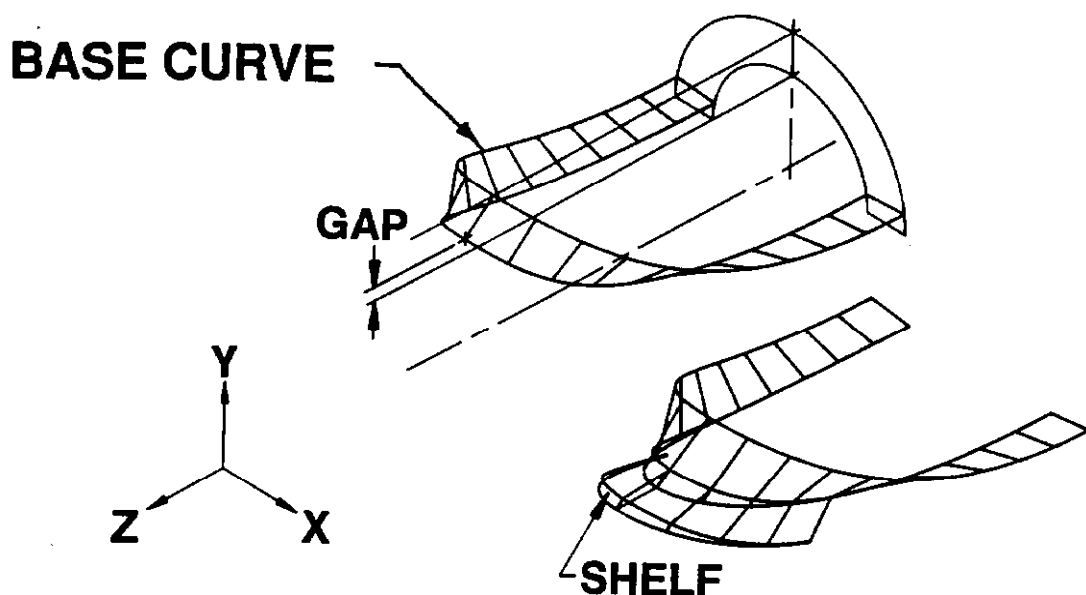


Figure 4.

The base curve is described as an elastica, a curve into which the central line of a thin elastic rod of circular cross section will be bent when forces and couples are applied to its ends only. The curve then satisfies the condition that it have the minimum possible strain energy, subject to certain constraints. It is, in our case, confined to a cylindrical surface and must satisfy certain initial and final conditions. These conditions are:

- a.) The line must begin at a point on the surface of the cylinder and be pointing in the direction of the positive z axis (see Figure 5). This point is determined by the magnet cross section.
- b.) The line must end at a point on the top center of the cylinder (at a value of $x=0$) and be pointing in the direction of the negative x axis (see Figure 5). This point is determined by magnetic considerations.

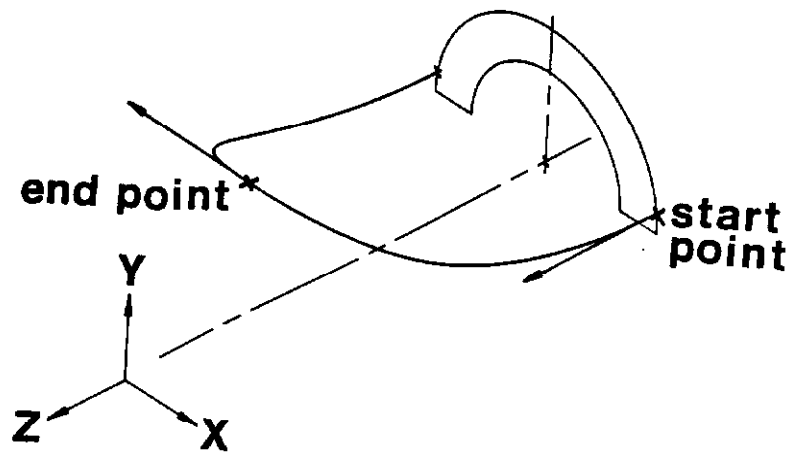


Figure 5.

Once the base curve has been made, a developable surface is created from it.

Creating the Developable Surface

- 1.) A set of closely spaced points is placed on the curve (P_1, P_2, \dots, P_n).
- 2.) Vectors (V_1, V_2, \dots, V_n) are drawn from the points in such a way that they sweep out a certain surface called the rectifying developable* of the curve. It is by definition perpendicular to the direction of curvature of the curve at every point. The cable is modeled by an infinitely thin strip in this surface along the curve.
- 3.) The cables are trimmed at the appropriate cable width (L). The trimmed edge is defined as the "free edge" of the strip.

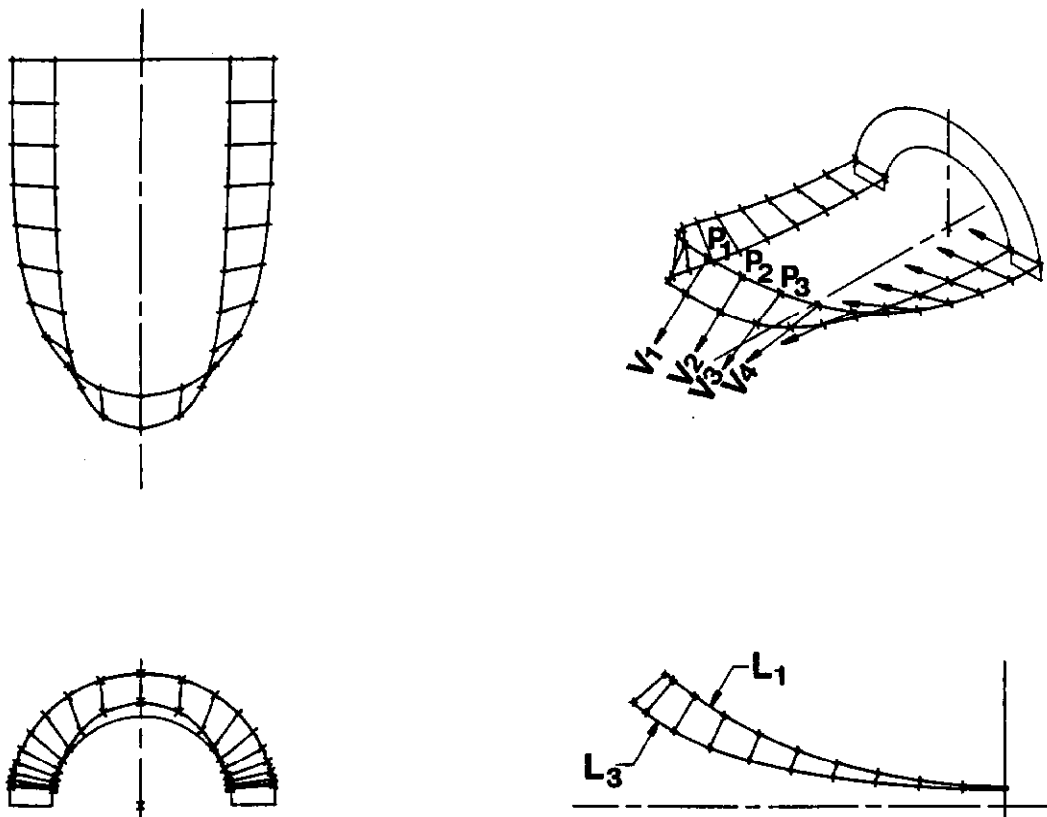


Figure 6. The Developable Surface

We now have a surface which is subject only to stresses due to the bend the easy way and the twist.

*See reference 1, section 3.

So:

The program prompts the designer for the values shown in Figure 7:

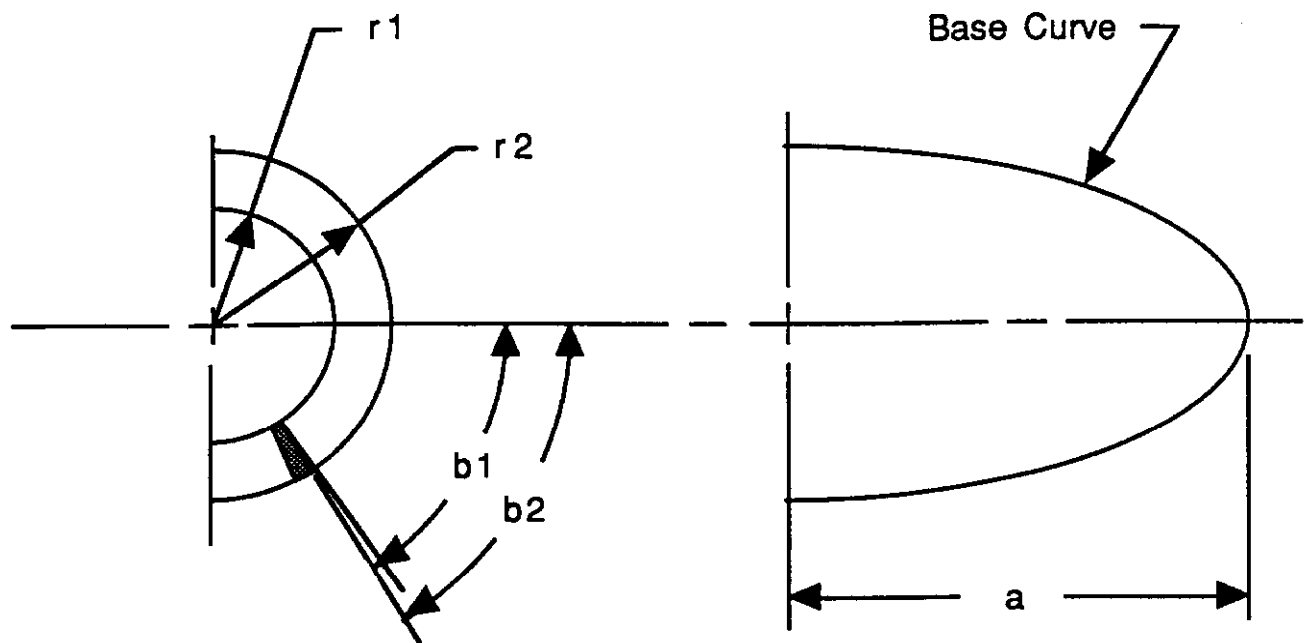


Figure 7.

It then automatically creates the surface. The output consists of a set of xyz coordinates which describe a set of points on the inner and outer edges of the surface. These edges represent the base curve and the free edge of the strip.

A problem with the developable surface:

It turns out that the rectifying developable vector, at the point of transition between the curve and straight section must, due to the conditions we have specified, intersect the bore centerline (see Figure 8).

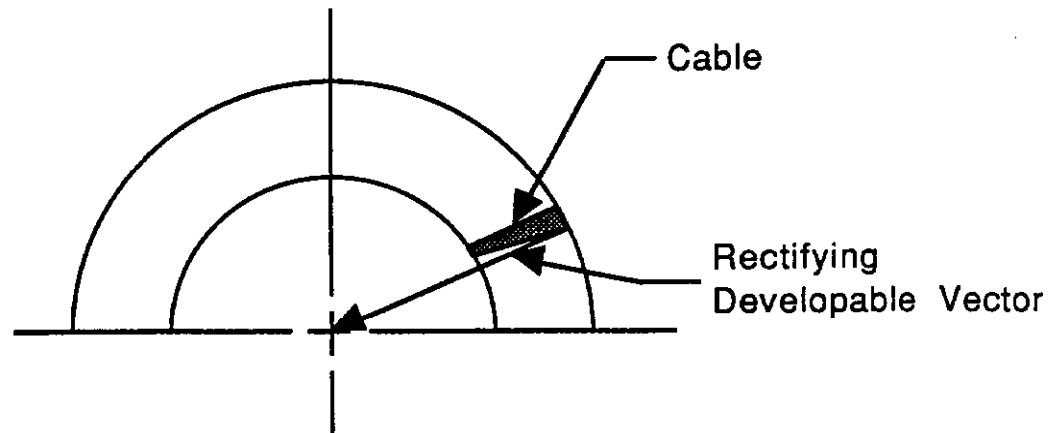


Figure 8.

The turns generally are not positioned radially with respect to the bore. It is therefore impossible to make a true developable surface which meets all our specifications. We can, however, make something very close. The program has been adjusted for turns which are not radial.

- First a developable surface is created based on the assumption that the cable does lie radially.
- The strip is then rotated about the point on the outer surface until it is aligned with the actual cable angle. This twist is smoothly distributed along the length of the cable.

This causes three things to happen:

- 1.) The strain energy due to the "bend the easy way" changes.
- 2.) The strain energy due to the twist changes.
- 3.) A strain energy due to the "bend the hard way" is introduced (developability has been violated).

The present program calculates the $\Delta L/L^*$ that has been introduced by the rotation. Information on both $\Delta L/L$ and twist is then supplied to the operator. The designer can then see if the $\Delta L/L$ or twist have become unacceptably large.

The $\Delta L/L$ in both the hard and easy ways is proportional to the square root of the strain energy created by the bend in that direction. The twist is proportional to the square root of the strain energy due to twist. The actual strain energies cannot yet be calculated because the flexural rigidities of the cable are presently unknown.

The program will soon be modified to determine the strain energy created by each of the three motions. This will allow the designer to:

- 1.) Know which of the three motions is creating the most strain energy.
- 2.) Minimize the total strain energy of the strip taking into consideration all three components.

The flexural rigidity of the cable in both the hard and easy way as well as the torsional rigidity will need to be measured. The end program will then need as input the same prompts which are now required plus the flexural rigidity in both directions and the torsional rigidity of the strip. It will output a least-stress strip based on the proper geometric constraints.

The program, then, currently gives priority to two parameters. It eliminates the bend the hard way of the strip by use of the developable surface. It minimizes the bend the easy way of the base curve by use of the elastica. These two parameters are minimized at the expense of the remaining ones. The free (inner) edge of the cable is typically forced into a narrower shape no longer optimal with respect to its total easy way strain energy. Twist also becomes more severe. This is considered an acceptable tradeoff. We will be able to optimize this tradeoff when we know the relative values of the three flexural rigidities. At present we must rely on past experience and empirical data from previous magnets to determine whether the deformations are acceptable. Experience in cable winding and some preliminary tests using SSC inner cable indicate that insulation breakdown begins to occur when the $\Delta L/L$ exceeds .40 or when the twist exceeds 90 degrees/in.

An analysis program will soon be completed which can be used with any magnet end. This will allow the strain energy of a magnet end not created by the Cook program, e.g. Tevatron, to be calculated. This could in turn help us understand what strain energies are acceptable.

*see Reference 2, p.2 for brief description of $\Delta L/L$

Flaws in the program:

- It is based on a model of a homogeneous, infinitely thin strip and not the composite of shapes and materials which make up a real cable.
- It is based on the elastic properties of the strip. We may be subjecting the cable to inelastic stresses.
- The twist direction is different on each side of the bore centerline. Since the cable is spiral wound, its torsional rigidity may be different depending on which way it is twisted. This could cause the ideal surface to look different on either side of the centerline.

End Parts Materials and Manufacturing

All end parts are presently made of G-10. They are produced by numerically controlled machines. The machining process is very time consuming and expensive.

Different manufacturing methods will be needed if parts are to be produced in large quantities. Parts have been molded from a few materials. No success has been achieved in finding a moldable, nonconducting material which withstands the forces involved in curing and operating a magnet.

One alternative is to cast the parts from a non-magnetic metal and coat them with an insulating material. Fermilab has made a set of end parts for an SSC dipole from aluminum. Suitable coatings for the metal parts are being sought. They will be used in short models.

Metal end parts could solve another problem. The present G-10 keys, although strong enough to withstand the pressures during collaring and magnet operation, are not strong enough to withstand the curing pressures. As a result a metal "winding key" must be used during winding and curing. It is replaced with a G-10 key before collaring. This process requires the first turn to be broken away from the rest of the cured coil. This turn is never re-molded to the coil. A metal key would withstand curing pressures and consequently not need to be removed.

Other Cross Sections

This end program was designed for use with SSC magnets. It could be used for any $\cos\theta$ magnet coil. The coil cross section dimensions and the end current block lengths need to be known to determine the end curves..

Table 1. shows $\Delta L/L$ and twist values for some possible turns in High Field Dipoles. Various bore diameters and cable widths are shown. Curves for each bore diameter are calculated for two start angles. The "start angle" refers to the angle from the vertical to the base curve at the end of the straight section as shown in Figure 9. The 20 degree start angle is similar to a pole turn. The 70 degree angle is similar to a turn near the parting plane. Both 4 and 5 cm. bores are shown with .366 and .500 cable widths. For simplicity, all turns except those in row 21 are assumed to point toward the center of the bore in the cross section, making true developable surfaces possible. Tevatron and SSC inner coils are used as a reference.

Two different methods of creating the curves are shown. The "traditional method" is similar to the Tevatron end in that the cable is held vertical at the center of the turn (see Figure 1.), although the base curve was initially created using the new program. The $\Delta L/L$ values using the traditional method should be similar to those that would be created by the method used for the Tevatron magnets. The "Cook method" is that which uses the elastica and developable surface as has been described on pages 4 through 7. The $\Delta L/L$ using this method will be zero as long as the turn points toward the bore centerline in the straight section. The twist will be greater for the Cook method than for the traditional method.

Total twist is the amount that the cable is twisted from the time it leaves the straight section until it crosses the center of the bore (from the start point to the end point in Figure 5). Maximum twist rate is the highest rate that the cable is twisting over any specific incremental length (approximately 10%) of the cable perimeter. Overall $\Delta L/L$ is the total difference between the base curve and the free curve divided by the length of the base curve. Extreme $\Delta L/L$ is the largest $\Delta L/L$ that occurs in any increment of the strip. It is important to distinguish between the "overall" and "extreme" $\Delta L/L$. Other programs which make a "constant perimeter" end may eliminate the overall $\Delta L/L$ but ignore the incremental $\Delta L/L$ values which may occur at intermediate points along the strip. These can cancel each other and make the overall $\Delta L/L$ small while overlooking large deformations at intermediate points in the conductor path.

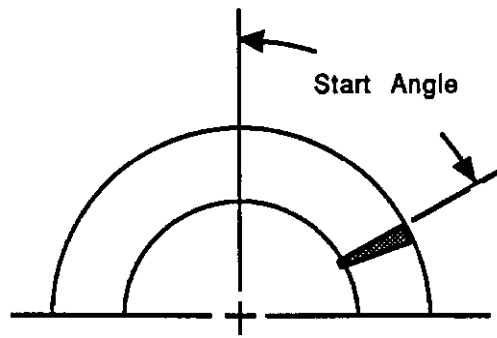


Figure 9.

Rows 1 thru 4 show a cable width and bore diameter identical to the Tevatron dipole. Rows 1 and 3 use the traditional method. These rows should therefore have $\Delta L/L$ and twist values similar to that which exist in the actual Tevatron magnets. Rows 5 through 8 show a cable width and bore diameter identical to the SSC inner coil. Rows 6 and 8 use the Cook method. These rows should therefore have $\Delta L/L$ and twist values which are similar to that which is used in SSC inner coils. Both Tevatron and SSC coils have been wound successfully. Rows 1,3,6 and 8 can be used as a reference. Rows 9 thru 21 show other possible cross sections.

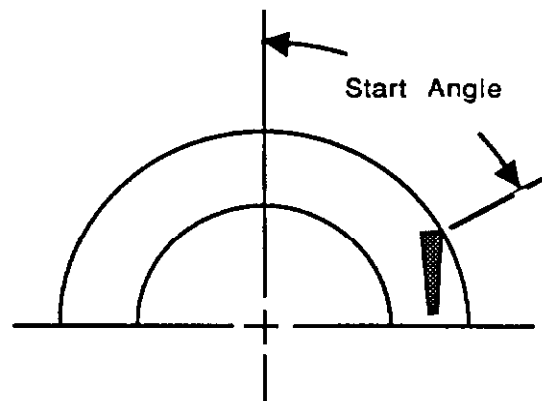


Figure 10.

Example	Row No.	Method of creating curve	Total Twist (degrees)	Maximum Twist Rate (degrees/in.)	Overall $\Delta L/L$	Extreme $\Delta L/L$
.307 cable 3 in. bore 20 deg. start angle (Tevatron inner coil)	1	Traditional	-10	-18	-.0764	-.3119
	2	Cook	-28.8	-46	0	0
.307 cable 3 in. bore 70 deg. start angle (Tevatron inner coil)	3	Traditional	-36.395	-24	-.0684	-.2062
	4	Cook	-82.65	-42	0	0
.366 cable 4 cm. bore 20 deg. start angle (SSC inner coil)	5	Traditional	-11.53	-43	-.1009	-.8726
	6	Cook	-27.4	-59	0	0
.366 cable 4 cm. bore 70 deg. start angle (SSC inner coil)	7	Traditional	-39.53	-28	-.1006	-.464
	8	Cook	-81.34	-52	0	0
.500 cable 4 cm. bore 20 deg. start angle	9	Traditional	-11.35	-37	-.0691	+.8906
	10	Cook	-27.22	-53	0	0
.500 cable 4 cm. bore 70 deg. start angle	11	Traditional	-38.23	-29	-.1009	-.6041
	12	Cook	-81.82	-52	0	0
.366 cable 5 cm. bore 20 deg. start angle	13	Traditional	-11.61	-38	-.0913	-.7094
	14	Cook	-27.49	-51	0	0
.366 cable 5 cm. bore 70 deg. start angle	15	Traditional	-39.98	-22	-.0892	-.3762
	16	Cook	-81.2	-42	0	0
.500 cable 5 cm. bore 20 deg. start angle	17	Traditional	-11.44	-33	-.0974	-.7432
	18	Cook	-27.32	-46	0	0
.500 cable 5 cm. bore 70 deg. start angle	19	Traditional	-38.98	-23	-.1038	-.4960
	20	Cook	-81.53	-42	0	0
.500 cable 5 cm. bore 70 deg. start angle (twisted as in Fig. 10 to resemble TAC style cross section)	21	Cook	-8.48	-9.9	+.1538	+.6397

Table 1.

Results

The Tevatron cross section can be acceptably wound with either method (rows 1 thru 4) although the deformations ($\Delta L/L$) are quite high using the traditional method. The traditional method cannot be used with the SSC inner coil (rows 5 and 7), although the Cook method can (rows 6 and 8). All other cross sections have unacceptable extreme $\Delta L/L$ values if wound by the traditional method (rows 9 thru 20). All appear to be acceptable if the Cook method is used. Pole turns are in general more highly deformed than turns near the parting plane.

The examples which use both a wider cable and larger bore are a likely possibility for a high field magnet (rows 17 thru 20). The wider cable would tend to make stresses higher (as compared to the SSC inner coil) while the larger bore would tend to decrease stresses. It appears that the effects from the bore diameter increase are dominant. Deformations for this cross section are smaller than those for the SSC. It seems then that a cross section using these parameters presents no problems for end winding.

Row 21 displays a turn near the parting plane which is wound in the manner of a TAC cross section (see Figure 10.). This method poses a problem. The turn must digress very far from developability, creating very large $\Delta L/L$ values even if the Cook program is used. It is not clear that the present format can be used to successfully create an end for the TAC cross section.

Conclusion

Coil end design, although always a concern, has become a more severe problem. Higher magnetic fields, smaller bore diameters and wider cables have all contributed to high stresses in the coil ends. Traditional methods have proven unacceptable for winding the ends of some high field magnets. New methods have been developed which create lower stress paths for the cables, making them easier to wind. These methods help to make conductor placement on the ends accurate and reproducible. They also make the design and manufacturing of ends for high field magnets more efficient.

References

- 1.) An Application of Differential Geometry to SSC Magnet End Winding
J. M. Cook, Argonne National Laboratory. (Preprint)
- 2.) Analytical Solutions to SSC Coil End Design. R. C. Bossert, J. S. Brandt, J. A. Carson, H. J. Fulton, G. C. Lee, Fermi National Accelerator Laboratory, J.M. Cook, Argonne National Laboratory, presented at the IISCC, February 8-10, 1989, New Orleans, La.
- 3.) The High Field Superferric Magnet J. C. Colvin et.al., Texas Accelerator Center. Nuclear Instruments and Methods in Physics Research A270 (1988) 207-211 North-Holland, Amsterdam.